CORRELATIONS WITH PHOTONS IN HEAVY-ION COLLISIONS

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We present a study of two-particle correlation functions involving photons and neutral pions in proton-proton and lead-lead collisions at the LHC energy. The aim is to use these correlation functions to quantify the effects of the medium on the jet decay properties.

1 Introduction

Electromagnetic probes have long been thought to be useful to detect the formation of quark-gluon plasma in ultrarelativistic heavy-ion collisions [1,2] and many observables involving photons can be used, since the photon can in principle be used to tag the energy of the recoiling jet. So, by comparing pp and PbPb correlations, one hopes to learn about medium effects in heavy ions collisions. Then, observing a particle recoiling from the photon gives information on the fragmentation properties of this recoiling jet.

2 Model

At leading order (LO) of QCD, the basic two-particle cross section from which we can construct various observables can be written as [3]:

$$\frac{d\sigma^{AB\to CD}}{dp_{T3}dy_3dz_3dp_{T4}dy_4dz_4} = \frac{1}{8\pi s^2} \quad \sum_{a,b,c,d} \quad \frac{D_{C/c}(z_3,M_F)}{z_3}\frac{D_{D/d}(z_4,M_F)}{z_4}\; k_{T3}\;\delta(k_{T3}-k_{T4}) \\ \frac{F_{a/A}(x_1,M)}{x_1}\;\frac{F_{b/B}(x_2,M)}{x_2}\quad |\overline{M}|^2_{ab\to cd} \tag{1}$$

The medium produced in heavy-ion collisions affects this cross-section by two principal effects, namely: the initial state effects and the final state effects.

2.1 *Initial state effects*

These effects result from the modification of the structure functions by the shadowing and anti-shadowing effects which are hard to calculate theoretically. So, we use here the parametrization of Eskola *et al.* [4], who tabulate a function $S_{a/\mathrm{A}}(x, M)$ in which quarks and gluons are treated separately and relates the PDFs in nucleon N to those in a nucleus A via

$$F_{a/\mathrm{A}}(x, M) = S_{a/\mathrm{A}}(x, M)\, F_{a/N}(x, M) \tag{2}$$

Nuclear effects in PDFs produce small changes in high-p_t particle production at RHIC and LHC, "at most 25% ".

2.2 *Final state effects*

In a medium, quarks and gluons lose energy by radiating gluons. Their fragmentation is modified (See BDMPS) [5,6]. One can define a medium-modified fragmentation function (FF) $D^{med}_{D/d}(z_d, M_F, k_{T_d})$ which is calculated from the medium-induced BDMPS gluon spectra $dI/d\omega$.

$$z_d\, D^{med}_{D/d}(z_d, M_F, k_{T_d}) = \int_0^{k_{T_d}(1-z_d)} d\epsilon\; \mathcal{D}_d(\epsilon, k_{T_d})\; z^*_d D_{D/d}(z^*_d, M_F) \tag{3}$$

where $z_d = \frac{p_{Td}}{k_{Td}}$ and $z^*_d = \frac{p_{Td}}{k_{Td}-\epsilon} = \frac{z_d}{1-\epsilon/k_{Td}}$. The BDMPS energy loss distribution is characterized by the energy scale [5,7,8].

$$\omega_c = \frac{1}{2}\,\hat{q}\, L^2 \tag{4}$$

The so-called gluon transport coefficient $\hat{q}$ reflects the medium gluon density and L is the length of matter covered by the hard parton in the medium.

2.3 *Medium-modified fragmentation functions*

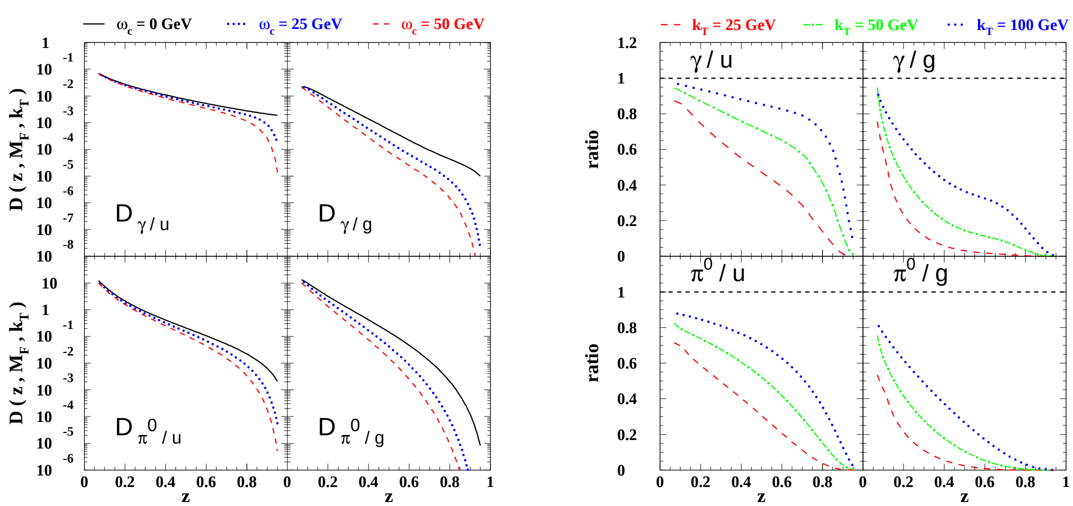

Figure 1: (*left*): *Medium-modified FFs* $D^{\mathrm{med}}_{D/d}(z_d, M_F, k_{Td})$ *for various energy loss scales,* $\omega_c = 0$, *25 and 50 GeV. The parton energy is* $k_T = 50$ *GeV and (right): Ratio of medium-modified* ($\omega_c = 50$ *GeV) over vacuum* ($\omega_c = 0$ *GeV) FFs for various parton energy,* $k_T = 25, 50$ *and 100 GeV. The fragmentation scale is set to* $M_F = p_T/2$

We observe that effects of parton energy loss become more pronounced as z gets larger, due to the restricted available phase space in Eq. (1). Gluons lose more energy than quarks do from their larger color charge ($C_g = 3$, $C_q = 4/3$). In the high energy limit $k_T \gg \omega_c$ and thus $z^* \simeq z$, the medium effects vanish and the ratio approaches one.

3 The correlations

We construct from Eq. (1) the following observables [9]:
- the invariant mass of the particle pair, m_{34}^2
- the transverse momentum of the pair, $q_T = |\vec{p}_{T3} + \vec{p}_{T4}| = k_T \; |z_3 - z_4|$
- the relative transverse momentum of the particles (also called momentum balance), $z_{34} = -\frac{\vec{p}_{T3} \cdot \vec{p}_{T4}}{p_{T3}^2} = \frac{z_4}{z_3}$

Note that for direct photon, momentum fraction is $z_3 = 1$. For fragmentation photon, $z_3 < 1$ and is further reduced by medium-induced energy loss.

3.1 Phenomenology of $\gamma - \pi^0$ correlations

The photon can be produced directly and the recoiling jet fragments into a pion (labeled 1f), or both the photon and the pion are produced by fragmentation of partons (labeled 2f).

For LHC, we impose the following cuts: $p_{T_\pi} \geq 5$ GeV and $p_{T_\gamma} \geq 25$ GeV. We observe clearly in Fig.2 the

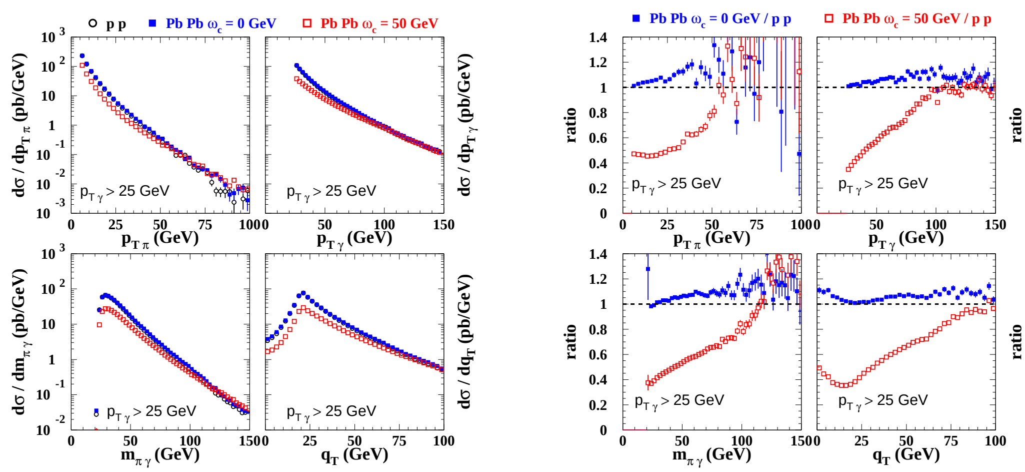

Figure 2: *(left): The four distributions in $\gamma - \pi^0$ production for p-p (open dots) and Pb-Pb scattering ($\omega_c = 0$ GeV: black squares; $\omega_c = 50$ GeV: open squares) at $\sqrt{s} = 5.5$ TeV. $|\eta_\gamma| < 0.5$, $|\eta_\pi| < 0.5$; cuts imposed are: $p_{T\gamma} > 25$ GeV, $p_{T\pi} > 5$ GeV. (right): The same as left Figure but the distributions are normalized to p-p case*

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expected effect of the suppression. Energy loss effects modify the distributions much more drastically.

3.2 Phenomenology of $\gamma - \gamma$ correlations

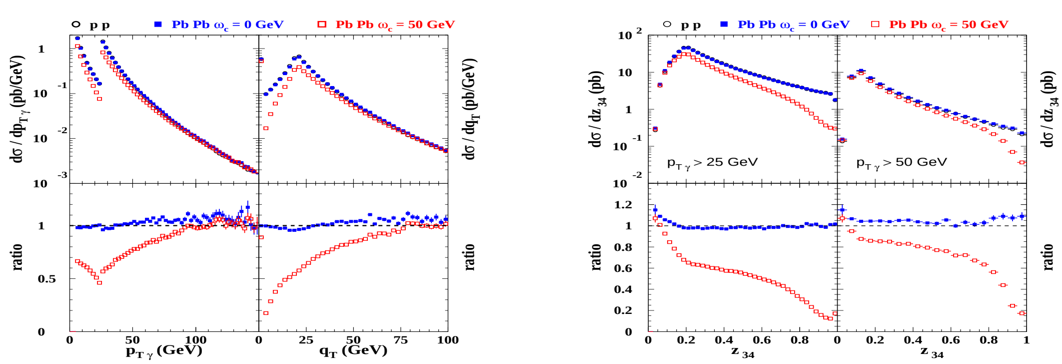

Figure 3: *(left): Top: The p_{T_γ} and q_T transverse momentum distributions in $\gamma - \gamma$ production for p-p (open dots) and Pb-Pb scattering ($\omega_c = 0$ GeV: black squares; $\omega_c = 50$ GeV: open squares) at $\sqrt{s} = 5.5$ TeV, with the same cuts as in Figure (2). Bottom: The same distributions normalized to the p-p case. (right): The z_{34} distribution in $\gamma - \gamma$ for p-p (open dots) and Pb-Pb scattering (for the same kinematical cuts). Bottom: The same distributions normalized to the p-p case.*

The new feature here is that both photons can be produced directly (*direct* process) in which case they are not affected by medium. The study of the $\gamma-\gamma$ correlations is made in the same kinematic regime as before, i.e. $p_{T_{\gamma_1}} > 25$ GeV and $p_{T_{\gamma_2}} > 5$ GeV. In particular, we observe in Fig.3 (*right: Bottom)* a strong suppression as z_{34} gets close to 1, as expected from the restricted phase space in Eq. (3). Assuming the 1-fragmentation dominates, we have at LO $z_{34} \simeq z$. The distribution $d\sigma/dz_{34}$ is thus reminiscent of the photon fragmentation function, $D_{\gamma/k}(z_{34})$. This observable offers therefore a "direct" access to the medium-modified fragmentation functions. On the same Figure (*left panel*), the photon p_T spectra are also determined (*lower left*), the quenching is maximal around the upper cut. Indeed, as p_T approaches the upper cut from "below", events with larger z are selected, $p_{T1} \simeq p_{T2}$, where energy loss effects are most pronounced.

The z distributions in Fig. 4 appear to follow closely the input functions in Fig. 1 and therefore provide

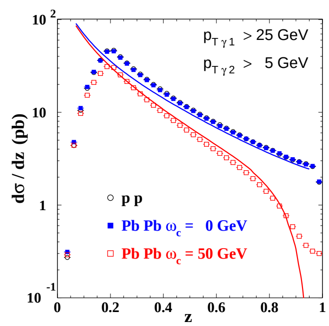

Figure 4: *Example of a photon-photon correlation function at LHC* [8].

a way to probe in detail the jet energy loss mechanism. The same measure involving a pion (photon-pion correlation) has a larger rate but leads to a more complex picture because of the convolution with the production processes: 1f at small z_{34} and 2f at large z_{34}.

Conclusions

We have discussed various photon tagged correlations as a tool to study jet fragmentation in hot medium created in heavy-ion collisions. We show that significant effects could be expected at LHC energy both in the $\gamma - \pi^0$ and $\gamma - \gamma$ channel. The use of asymmetric cuts in the transverse momentum of both particles allow the possibility to map out the parton fragmentation functions modified by the medium. The variety of observables presented here should help constrain the underlying model for parton energy loss. We believe our present LO predictions to be valid roughly up to $z_{34} \simeq 0.8$.

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